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Experimental Demonstration of a 120-mm Ram Accelerator

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13. ABSTRACT *(Maximum 200 words)*

Ram acceleration is an emerging propulsion technology in which a projectile similar in shape to the centerbody of a ramjet aircraft engine is injected at high speed into a tube filled with a combustible gaseous mixture. As the projectile moves into the tube, under supersonic conditions, shocks occur on and around the projectile. If the gases are then ignited, either by the energy in the shock system or an external mechanism, the combustion around or behind the projectile can be self-sustaining. The net effect is to generate a localized high-pressure region around and/or behind the projectile which produces acceleration. Work at the University of Washington, Seattle, has demonstrated velocities in excess of 2.6 km/s in 38-mm caliber, while theory predicts velocities above 7 km/s may be obtainable.

The first successful ram acceleration experiment at 120-mm caliber is presented. Performance at this larger caliber was as predicted from scaling considerations. Reported experiments have shown that propellant mixing by partial pressure is a viable alternative to more complex mixing schemes for obtaining homogeneous propellant mixtures in ram accelerators. The usefulness of inert firings to analyze obturator performance and shock/pressure structure in ram accelerators has been further validated. Finally, the scaling potential of ram acceleration has been firmly established with the first successful test at 120-mm caliber.

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1. INTRODUCTION

The Weapons Technology Directorate of the U.S. Army Research Laboratory (ARL) (formerly the U.S. Army Ballistic Research Laboratory [BRL]*) has been conducting an experimental and computational effort aimed at developing sufficient understanding of the ram acceleration process to successfully scale the process to larger caliber guns and launch masses. This report presents the first results from the experimental scaling effort with a 120-mm ram accelerator. Scaling discussions based on data from three bore diameter accelerators are presented. Additional background on the ARL ram accelerator can be found in Kruczynski (1991a, 1991b, 1992) and Nusca (1991a, 1991b).

2. PROJECTILE, FACILITY, AND INSTRUMENTATION

The ARL ram accelerator program has been dubbed HIRAM or Hybrid Inbore Ram accelerator for its use of combined propulsion technologies (conventional solid propellant projectile launch followed by ram acceleration). The current projectile design is a geometric scale-up of one of the most extensively tested designs of the University of Washington (UW). The basic projectile is shown in Figure 1. Currently, the projectile is made from a high-strength aluminum alloy (7075-T6) and has a mass of 4.29 kg.

The accelerator tubes are made from retired 120-mm M256 tank guns appropriately machined and mated. Transition from the conventional solid propellant launcher to the ram accelerator is made through a transition/vent section. This section serves the dual purpose of decoupling the conventional launch gun from the ram accelerator (through a sliding interface) and venting the backpressure from the conventional charge combustion, which further assists in decoupling the two processes. The HIRAM facility was initially designed to accommodate five 4.7-m-long accelerator tubes for a total combined acceleration of 23.5 m. There is also allowance for future expansion to 60 m. Initial experiments reported here were performed using a single 4.7-m accelerator section. Gases are supplied from a bottle farm and diaphragm compressor capable of supplying gases at pressures up to 35 MPa (5,000 psi). All gas supply operations are handled remotely using solenoid-controlled, air-operated valves. A large vacuum pump is also installed near the accelerator to evacuate any part (or all) of the launch/vent/accelerator sections, when desired. Figure 2 shows a drawing of the primary facility.

* The U.S. Army Ballistic Research Laboratory (BRL) was deactivated on 30 September 1992 and subsequently became a part of the U.S. Army Research Laboratory (ARL) on 1 October 1992.

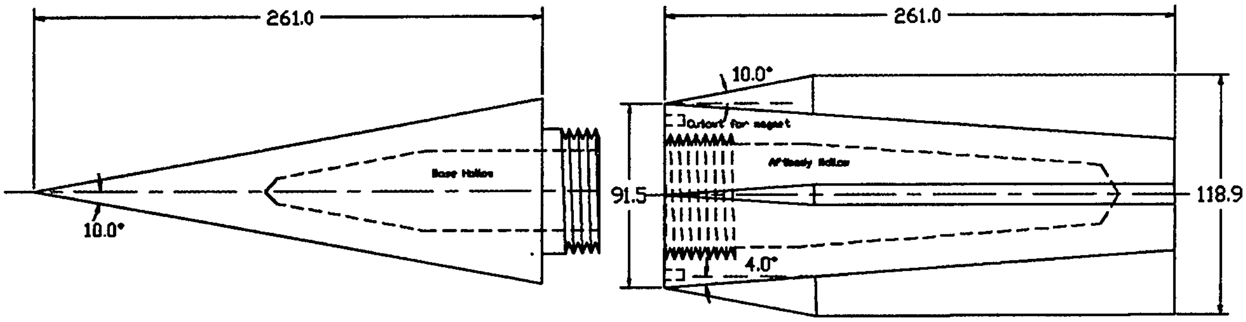

Figure 1. The 120-mm HIRAM projectile.

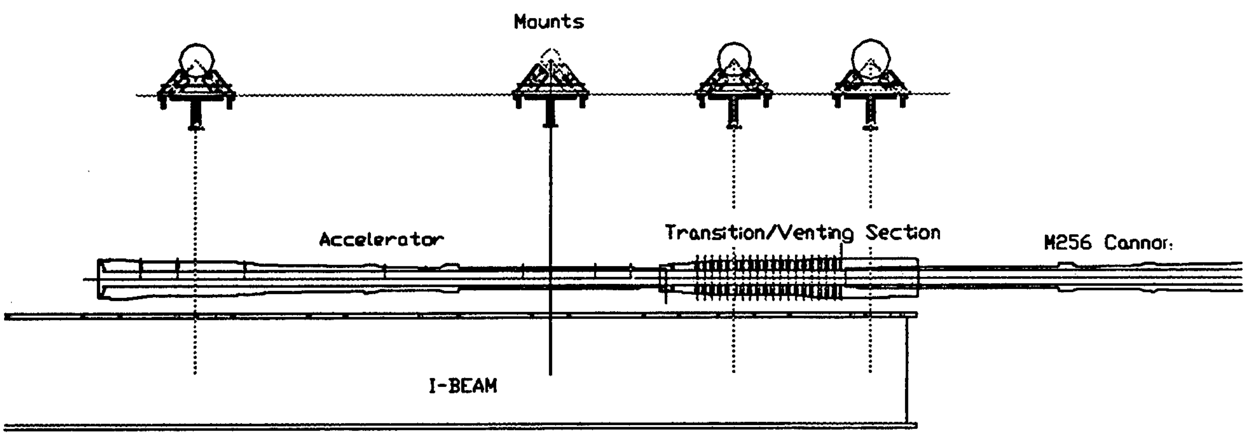

Figure 2. Primary HIRAM accelerator components.

Instrumentation within the accelerator tube and diagnostics available during HIRAM firings include tube wall-mounted quartz pressure transducers, photodiode light detectors, and electromagnetic sensors. In addition, high-speed movie and still-capture (smear) cameras are employed at various locations around the accelerator during firings. Samples of propellant mixes for later analysis may be taken (remotely) after filling the accelerator. Doppler radar, magnetic coils, and electro-optical sensor devices (sky screens) are used to measure projectile velocity after exiting the accelerator.

3. SCALING EFFECTS

3.1 Propellant Ignition and Induction Times. Early data from firings at the UW (Hertzberg, Bruckner, and Bogdanoff 1988; Bruckner et al. 1991; Knowlen, Bruckner, and Hertzberg 1992; Knowlen et al. 1992), the Institut Saint Louis in France (Giraud et al. 1992; Giraud, Legendre, and Simon 1992), and ARL indicated that geometric scaling required changes in propellant chemistry. At the time, it was thought that a relationship between geometry and combustion induction times existed (Kruczynski 1992). The relationship was thought to be such that for the same given propellant mixtures at the same pressures and with similar projectile entrance velocities, the onset of significant energy release will take place in similar timeframes. Thus, energy release that occurred on the afterbody of a smaller scale projectile may occur on the nose of a larger (and longer) scale projectile. Thus, these early experimental findings had prompted researchers to lower propellant ignition sensitivity as calibers increased as shown in Table 1.

Table 1. Typical Propellants for Several Ram Accelerators in Early Experiments

System Caliber (mm)	Propellant Mixture (typical)	Speed of Sound (m/s)	CJ* Velocity (m/s)	$\frac{Q}{C_p \Delta T}$ at Mach # = 3
38	$2.4CH_4 + 2O_2 + 5.8N_2$	363	1,700	5.01
90	$3CH_4 + 2O_2 + 7N_2$	364	1,574	4.39
120	$3CH_4 + 2O_2 + 10N_2$	361	1,448	3.72

Very recent experiments in the ARL 120-mm ram accelerator have revealed that large-caliber accelerators can operate at propellant energy levels equal to those of smaller caliber accelerators. These results will be reported in a future ARL report.

3.2 Propellant Charge Pressure. To date there have been limited data (see Figure 3) indicating that precharge pressures are related to combustion pressures around the projectile. That is, for higher propellant precharge pressures, higher combustion pressures and thrust are produced. However, these studies have been limited to precharge pressures of 5 MPa (750 psi). It remains to be seen if this trend

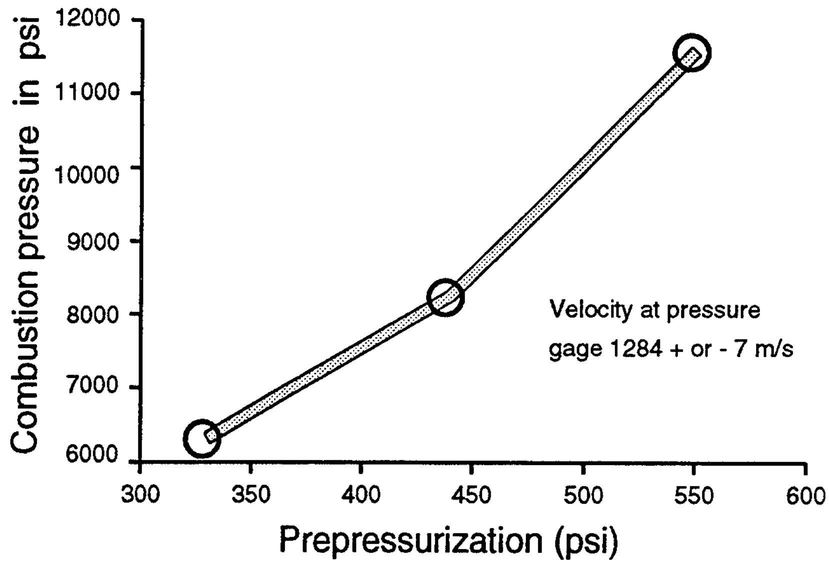

Figure 3. Combustion pressure vs. precharge pressure.

will continue at higher pressures. One possibility is that higher pressures will reduce reaction induction times so that progressively less ignitable (cooler) mixtures will be required to preclude premature energy release. The ARL HIRAM facility is the first ram accelerator capable of operation at significantly higher propellant precharge pressures, up to at least 10 MPa (1,500 psi), and we will evaluate this important parameter early in the research program (this has been done and will be reported separately).

4. FIRST EXPERIMENTAL RESULTS IN A 120-mm RAM ACCELERATOR

4.1 Propellant Mixing. The HIRAM system is the first ram accelerator to employ the relatively simple technique of partial pressure mixing to achieve desired propellant component ratios. As such, there was some concern about the ability to obtain accurate and homogeneous mixtures when the gases are injected separately into a ram accelerator. Table 2 presents results from two full-scale mixing tests in the first stage of the HIRAM accelerator, as well as from the first "live" propellant firing. In the HIRAM system, the gases are injected to promote mixing at three locations—one at each end and one in the center of each accelerator tube. Sampling or venting is done at a separate port located 0.405 m to the side of the center fill port. The data from the gas analysis reveal that the relative amount of each propellant component is reasonably close to that desired. However, since the mixtures were analyzed many hours after sampling, the homogeneity of the mixture at fill time is not assured (final mixing may be occurring in the sample bottle). Future efforts will be designed to analyze the mixtures within minutes of firing to further check the state of the tested gases.

Table 2. Partial Pressure Filling Analysis

Desired molar mixture ratio mixture and total pressure: $2O_2 + 10N_2 + 3CH_4$ at 51 atm (70 psi).						
Calculated/Experimental					Gas Chromatography (GC)	
Test No.	Gas[a]	Partial Pressure (psi)	Total Pressure (psi)	Volume Percent	Volume Percent (Concentration)	Percent Difference From Experimental
A[b]	Oxygen Nitrogen Methane	90 480 170	90 570 740	12.848 65.657 21.496	12.472 67.213 21.997	2.9 2.3 2.3
Implied molar mixture from CG: $1.8O_2 + 9.9N_2 + 3.3CH_4$						
B[c]	Oxygen Nitrogen Methane	100 490 160	100 590 750	13.179 66.425 20.392	14.010 66.987 20.649	5.9 0.8 1.2
C[d]	Oxygen Nitrogen Methane	100 490 160	100 590 750	13.179 66.425 20.392	13.300 70.000 18.000	0.9 5.1 11.7
Implied molar mixture from CG: $2.0O_2 + 10.5N_2 + 2.7CH_4$						

[a] Gases are listed in order of fill.

[b] Test No. A - Partial pressures from nonideal equation of state. Time from completion of chamber filling to withdrawal of sample was 2.5 min. The sample was analyzed within 45 min of being taken and again 18 hr later with essentially the same results. All sample (A and B) analyses were verified by duplicate testing.

[c] Test No. B - Partial pressures from ideal equation of state. A sample was taken 2 min after completion of chamber filling and analyzed 15 hr later.

[d] Test No. C - First live gas accelerator test (round 15). Partial pressures are from ideal equation of state. A sample was taken 1 min after filling and analyzed 19 hr later. Round 15 was fired immediately after taking the sample.

NOTE: The following are acknowledged sources of error:

- Partial pressures are rounded to the nearest 10-psi increment in these tests.
- No adjustment was made to allow for the volume of gas which gets trapped in the supply lines and is subsequently pumped into the chamber with the next gas (e.g., the nitrogen pushes in additional oxygen, while the methane pushes in additional nitrogen).
- The total error associated with sample preparation and CG analysis is ±2%.

4.2 Inert Gas Firings. Ram accelerators are unique for "gun like" systems in that the ignition and proper starting sequences can be studied in inert gases with reasonable expectation that this knowledge can be directly applied to "live" gas tests. A detailed study of these inert gas phenomena is given in Kruczynski and Nusca (1992). For brief comparative purposes, a tube wall pressure profile from an "unstarted" HIRAM projectile test sequence using inert gas (nitrogen) is shown in Figure 4. Note that shortly after entrance in the ram accelerator, the projectile is pushing a significant pressure wave ahead of itself. In combustible gas mixtures, these pressure waves would most likely produce combustion and higher leading pressures. Contrast the pressure profile of Figure 4 with that in Figure 5 of a properly started and running projectile in inert gas. Note that the projectile has little lead pressure activity and can clearly be seen separating from its obturator as noted by the low pressures between the projectile and the trailing obturator. Obtaining such cold starts is crucial to proper obturator development and eventual startup and acceleration in live propellants.

4.3 "Live" Gas Firings. Following a series of 14 shots through inert gases to characterize obturator performance and shock structure, the first firing of the HIRAM system with live gases was conducted. The propellant mixture used has been previously described in Tables 1 and 2. The projectile was injected into the HIRAM accelerator (4.7 m long) at 1,170 m/s from a conventional solid propellant gun (Kruczynski 1991b). Proper ignition and subsequent acceleration were achieved. Figures 6–11 show a series of pressure profiles as the projectile moved through the accelerator. These pressure profiles indicate that ram combustion occurred almost immediately upon entry into the accelerator and this combustion produced high pressures immediately behind the projectile throughout the accelerator. The velocity profile appears in Figure 12. The projectile accelerated from its entrance velocity of 1,170 m/s (Mach 3.2) to 1,419 m/s (Mach 3.9), which is just under the Chapman-Jouget (C-J) detonation speed (1,448 m/s) for this mixture. The projectile appeared to accelerate more quickly as it proceeded downtube and left the accelerator with full-ram combustion established as verified by high-speed photography. The velocity gain by the projectile matched predicted values based on scaled UW data.

5. SUMMARY

The first successful ram acceleration experiment at 120-mm caliber was conducted. Performance at this larger caliber was as predicted from scaling considerations. Reported experiments have shown that

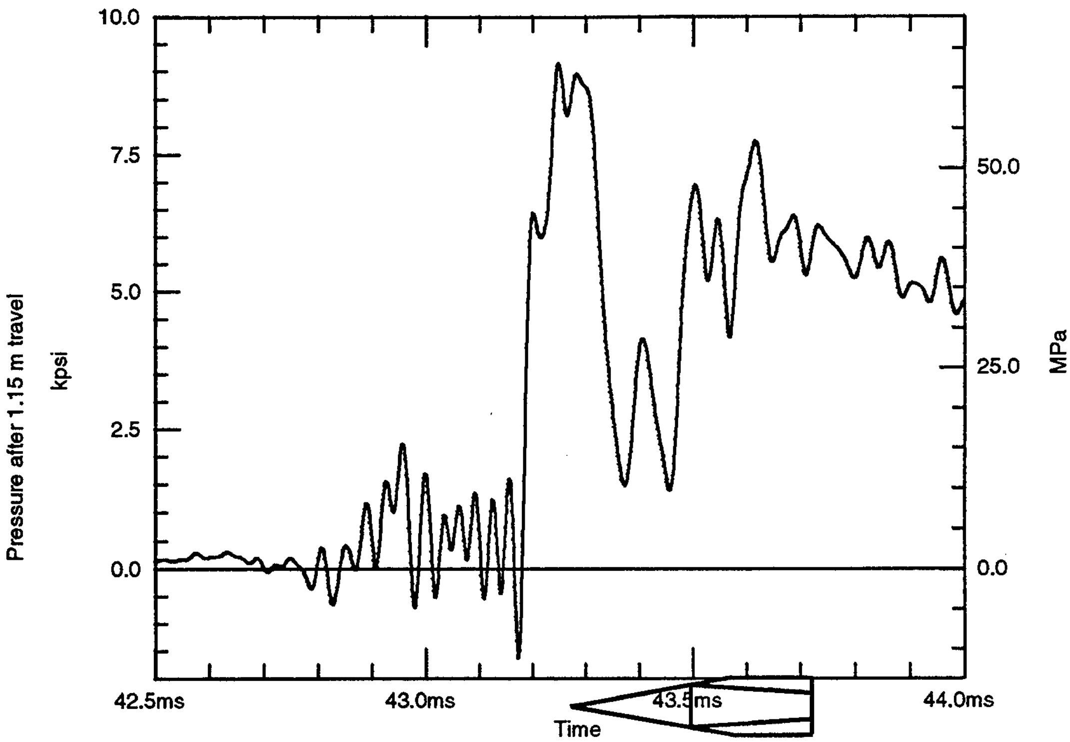

Figure 4. "Unstarted" projectile using inert gas (nitrogen). Note significant pressure wave activity in front of the projectile. Projectile is scaled to local velocity.

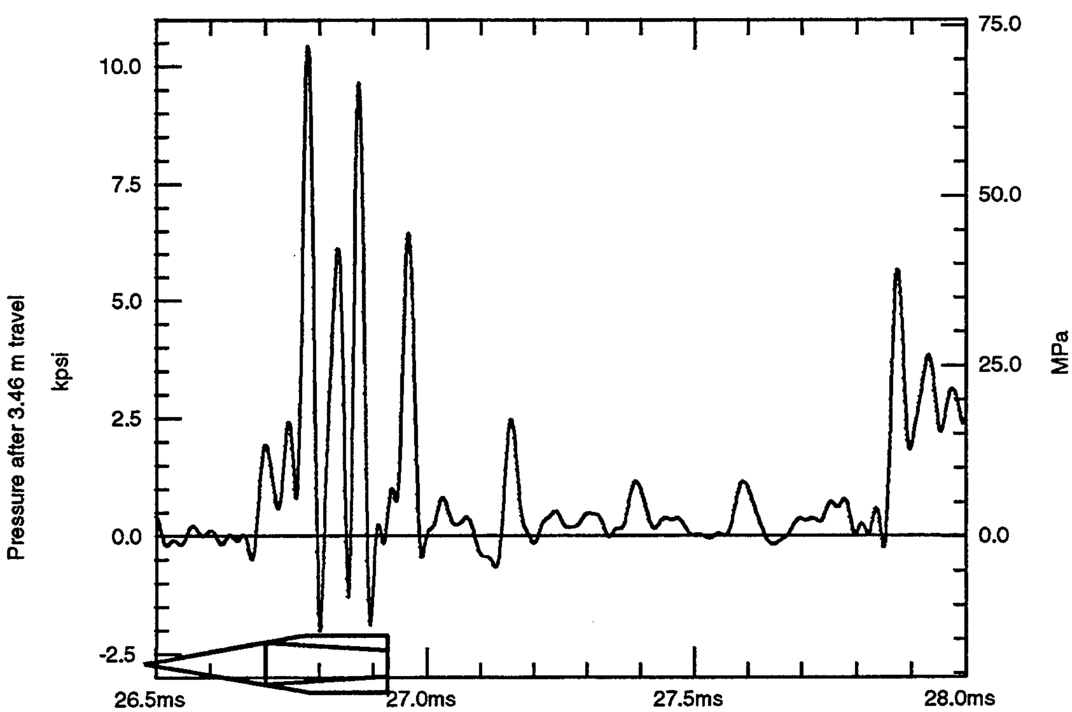

Figure 5. "Started" projectile using inert gas (nitrogen). Note little pressure wave activity in front of the projectile. Projectile is scaled to local velocity.

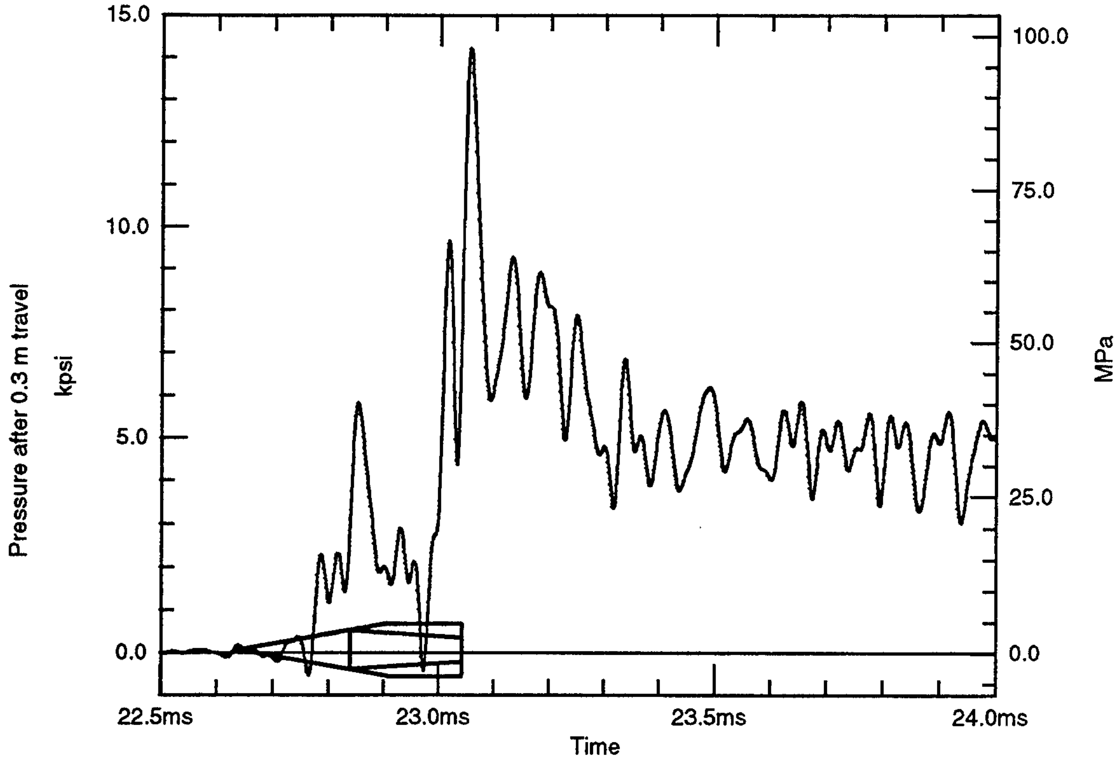

Figure 6. Ram combustion in a 120-mm accelerator after 0.3-m travel. Note high levels of pressure immediately behind the projectile indicating combustion (compare with Figure 5 with inert gas). Projectile is scaled to local velocity.

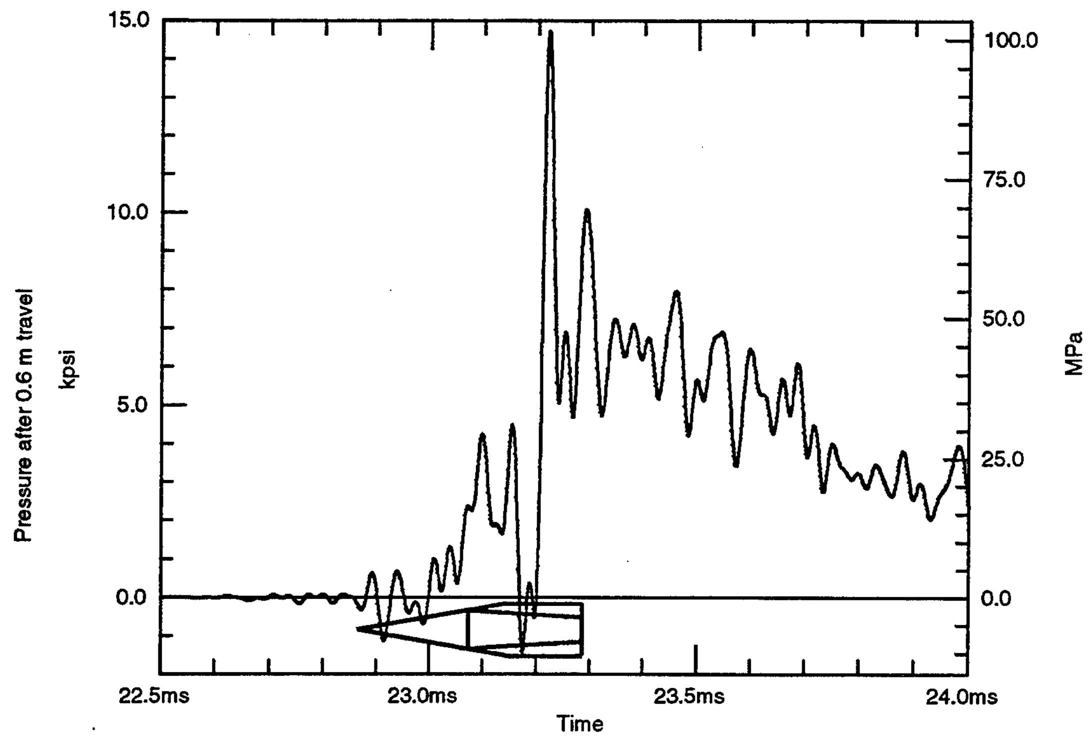

Figure 7. Ram combustion in a 120-mm accelerator after 0.6-m travel. Projectile is scaled to local velocity.

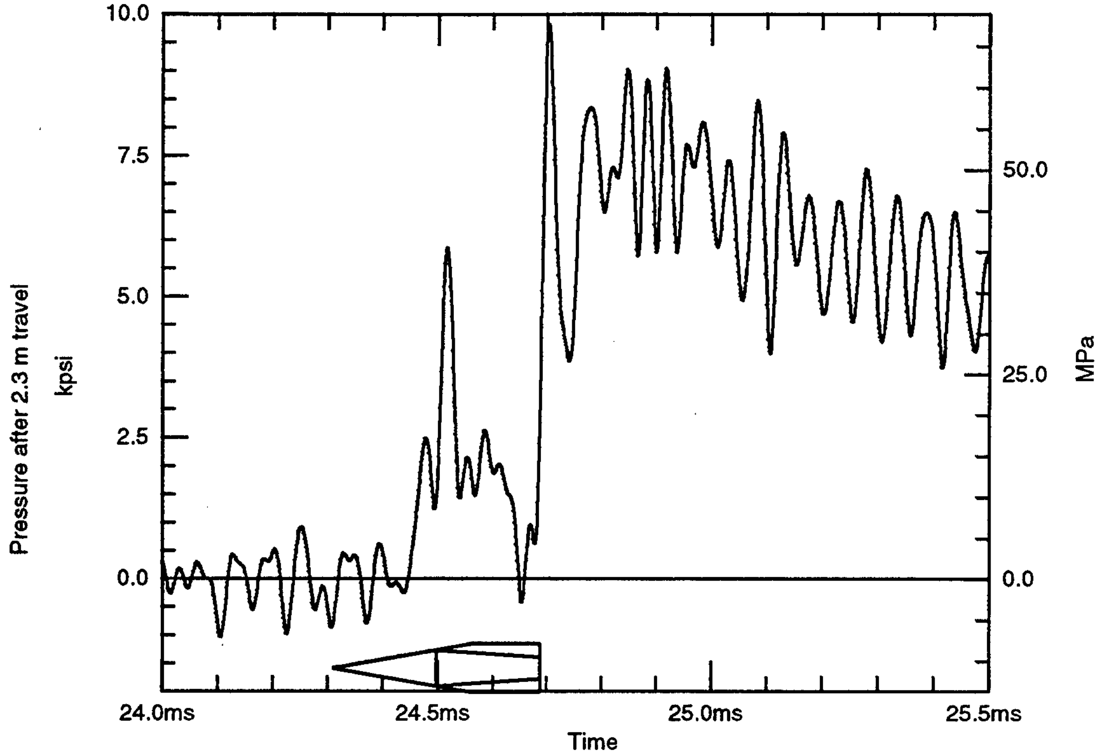

Figure 8. Ram combustion in a 120-mm accelerator after 2.3-m travel. Projectile is scaled to local velocity.

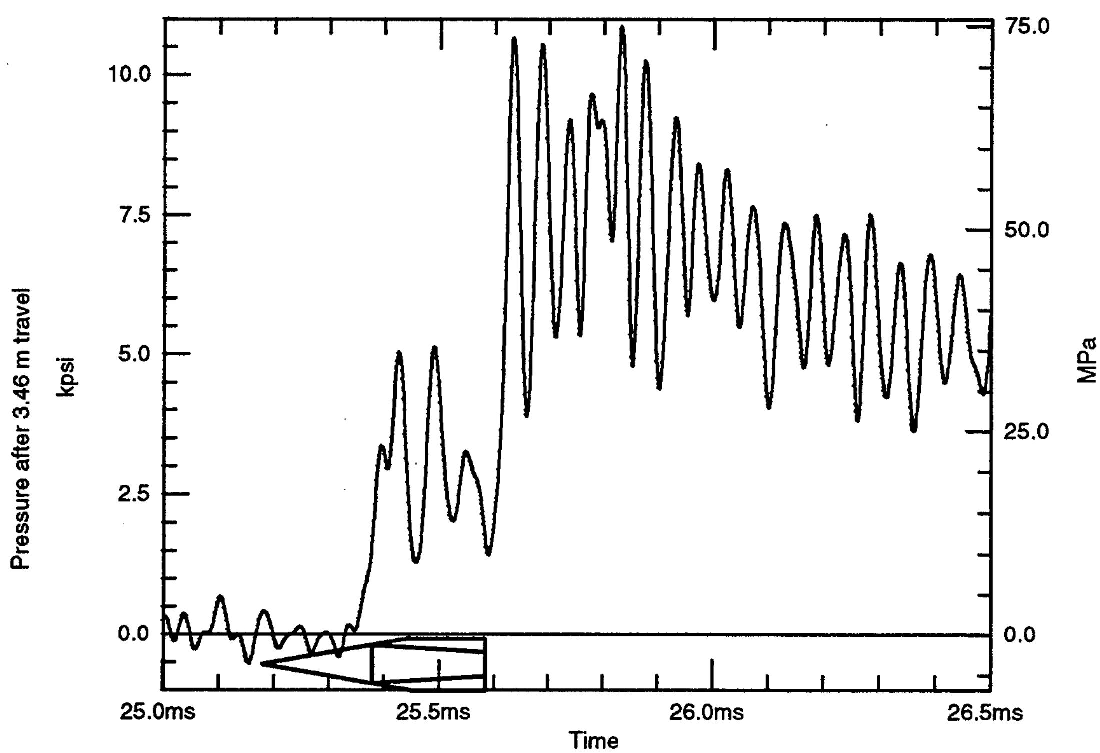

Figure 9. Ram combustion in a 120-mm accelerator after 3.46-m travel. Projectile is scaled to local velocity.

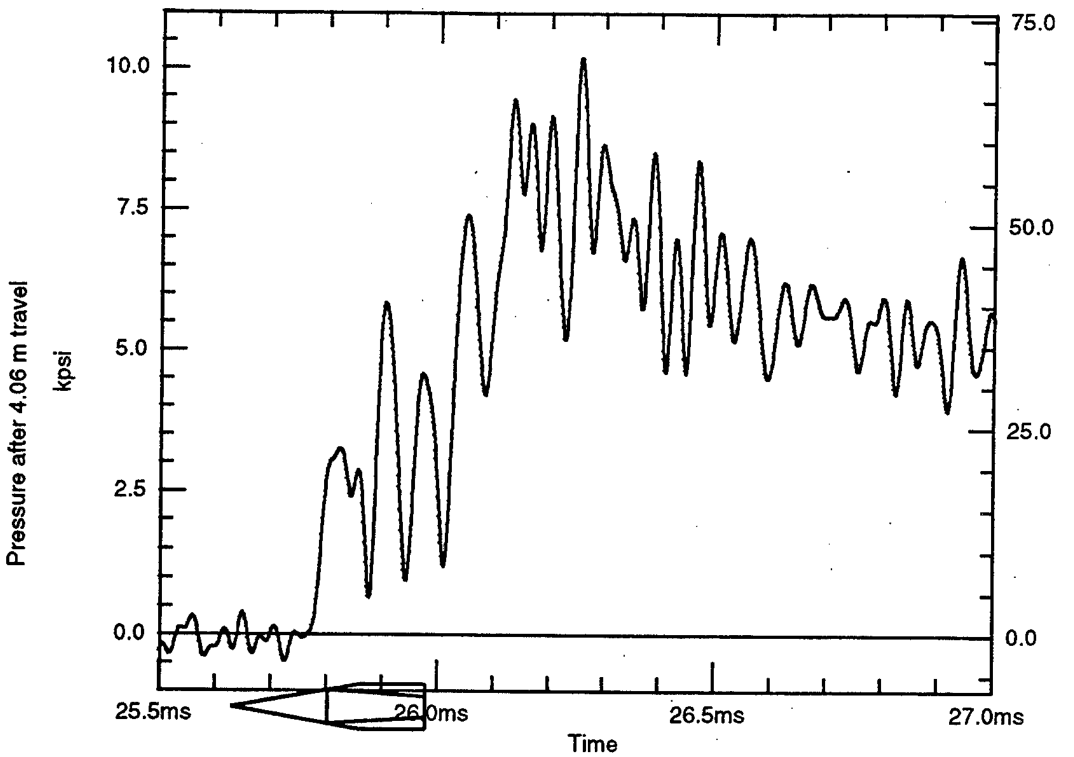

Figure 10. Ram combustion in a 120-mm accelerator after 4.06-m travel. Projectile is scaled to local velocity.

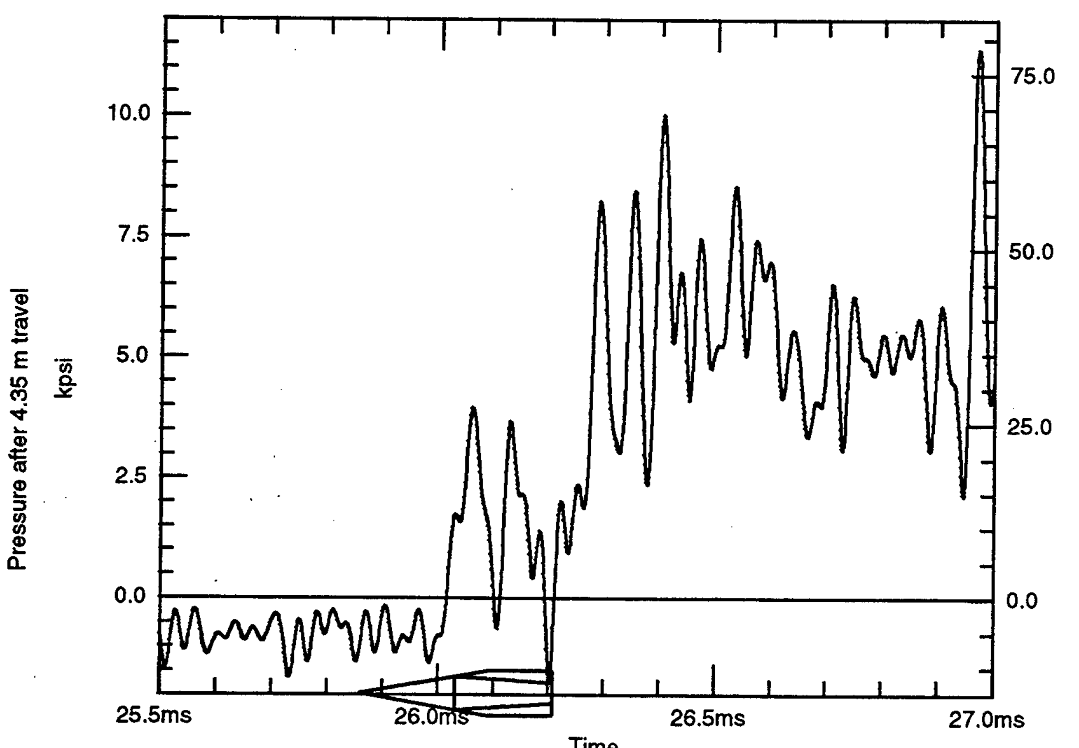

Figure 11. Ram combustion in a 120-mm accelerator after 4.35-m travel. Projectile is scaled to local velocity.

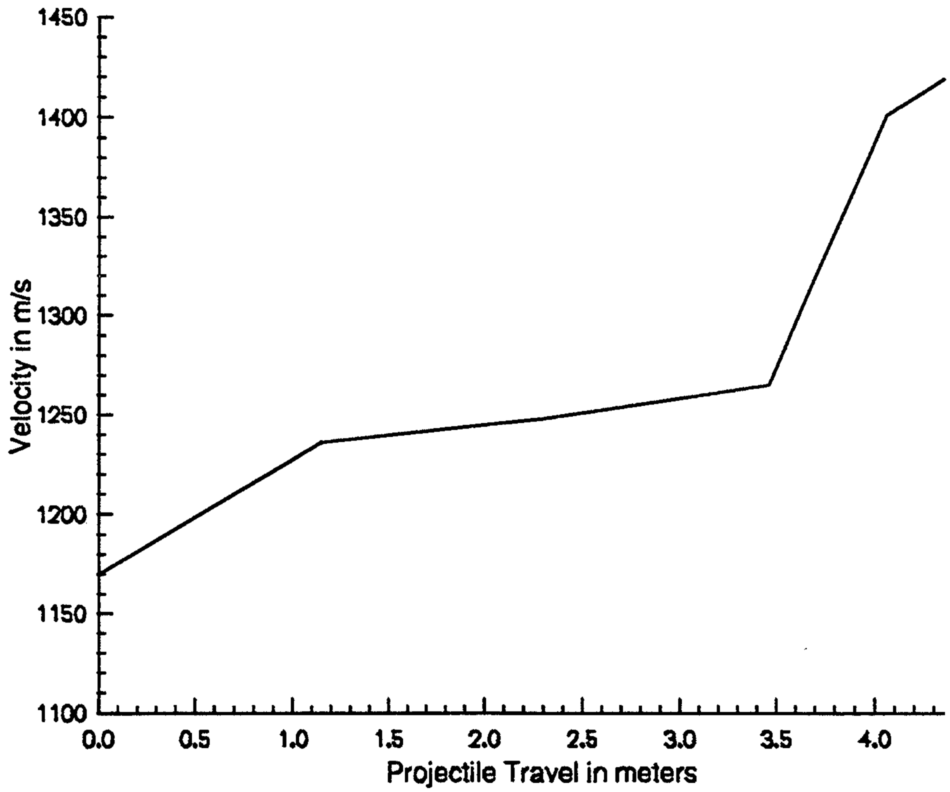

Figure 12. Plot of projectile velocity vs. projectile travel for 120-mm ram accelerator (round 15).

propellant mixing by partial pressure is a viable alternative to more complex mixing schemes for obtaining homogeneous propellant mixtures in ram accelerators. The usefulness of inert firings to analyze obturator performance and shock/pressure structure in ram accelerators has been further validated. Finally, the scaling potential of ram acceleration has been firmly established with the first successful test at 120-mm caliber.

6. FUTURE

Future plans for the HIRAM experimental program will include parametric evaluation of propellant fill pressure effects, examination of the process through optically clear tube sections, instrumented projectiles for base pressure and acceleration measurements, and application of other advanced diagnostic techniques for inbore flow measurements. In addition, the accelerator length will be increased to explore higher velocity/Mach number regimes.

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